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Prospects of renewable energy utilisation for electricity generation in Bangladesh

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Abstract

Bangladesh has been facing a power crisis for about a decade, mainly because of inadequate power generation capacity compared with demand and the ageing infrastructure of many existing power generation facilities. Only 20% of the total population are connected to grid electricity—25% in urban areas and a mere 10% in rural areas where 80% of the total population resides. Currently, most power plants in Bangladesh (representing 84.5% of the total installed capacity) use natural gas—the main commercial primary energy source, with limited national reserves—as a fuel. Electricity supply to low-load rural and remote areas is characterised by high transmission and distribution costs and transmission losses, and heavily subsidised pricing.

Renewable energy sources in Bangladesh, particularly biomass, can play a major role to meet electricity demands in the rural and remote areas of the country. The current study indicates that in 2003, the national total generation and recovery rates of biomass in Bangladesh were 148.983 and 86.276 Mtonne, respectively. In energy term, the national annual amount of the recoverable biomass is equivalent to 312.613 TWh. Considering the present national consumption of biomass, total available biomass resources potential for electricity generation vary from 183.865 to 223.794 TWh. Biomass energy potential in the individual districts of the country has been estimated for the planning small- to medium-scale biomass-to-electricity plants.

Keywords: Renewable energy; Electricity generation; Sustainability; Biomass; Bangladesh

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1. Introduction

World energy demand is likely to grow faster than the increase in population. In 2004, the total world-wide consumption of commercial primary energy sources was estimated at 10,224 Mtonne of oil equivalent (mtoe) [1]. Of the total, fossil fuels amounted to ~88%, whereas the shares of nuclear and hydroelectricity were small (Table 1). In addition to the well-recognised environmental impacts of the combustion of fossil fuels, there are two factors affecting their availability: the limited nature of their reserves and the security of supply. At current production rates, global proven reserves for crude oil and natural gas are estimated to last for 40.5 and 66.7 years, respectively [1]. Of all the global crude oil reserves, 81% are concentrated in eight countries, with about 61.7% in the Middle East and 22% in Saudia Arabia alone. Of all the natural gas reserves, 70% are in six countries, with about 40.6% in the Middle East and 35.7% in Europe and Eurasia. Although coal deposits are more evenly distributed, 89% of all coal reserves are in eight countries. More than half of Asian, African and Latin American countries import over 50% of all their commercial primary energy needs [1,2].

New and renewable energies will, therefore, become one of the world's main energy sources. At present, renewable energy contributes only 11% to world primary energy. It is, however, expected that 60% of all world energy will come from renewable energy sources by the year 2070 [3].

Electricity is a pre-requisite for technological progress and economic growth. Bangladesh has been facing a severe power crisis for about a decade. Currently, power

Table 1
Worldwide consumption of commercial primary energy in 2004 [1]

Source	Consumption	
	mtoe	% of total
Fossil fuels		
Oil	3767.1	36.84
Coal	2778.2	27.17
Natural gas	2420.4	23.67
Nuclear energy[a]	624.3	6.11
Hydro electricity[a]	634.4	6.21
Total	10,224.4	100.00

[a]Converted on the basis of thermal equivalence assuming 38% conversion efficiency in a modern oil-fired thermal power station to generate the same amount of electricity.

generation in the country is almost entirely dependent on natural gas (i.e. 84.5% of total electricity generation installed capacity [4]). At the current annual rate of growth of consumption of 10%, the national proven reserve of natural gas may not last more than 15–20 years [5].

Electrification of villages in remote areas usually requires large investment and leads to power losses associated with transmission and distribution networks. One of the great promises offered by the renewable energy technologies is their potential to provide electricity in areas not served by national power grids. The draft Renewable Energy Policy of Bangladesh, published in 2002, stated that renewable energy will take a vital role for off-grid electrification in the country. The main renewable energy resources in Bangladesh are biomass, solar, wind and hydropower. The hydropower potential of Bangladesh is low due to the relative flatness of the country. Most of potential sites for wind power utilisation are situated in coastal regions. Wind power generation in Bangladesh has certain limitations due to the lack of reliable wind speed data and the remarkable seasonal variation of wind speed. The country has good prospects of utilising solar photovoltaic (PV) systems for electricity generation, but the high capital investment cost of solar PV is a big barrier for adopting such systems. Biomass is the major energy source in Bangladesh and biomass utilisation systems represent a proven option for small- to medium-scale decentralised electricity generation.

Biomass is a versatile source of energy; it can be used as a solid fuel or converted into liquid or gaseous fuels. The utilisation of biomass, as a substitute for fossil fuels, plays also an important role in CO_2 mitigation. If grown in a sustainable manner, the production and utilisation of biomass create no net accumulation of CO_2 in the atmosphere [6]. During the next century, biomass energy is expected to offer cost-effective and sustainable opportunities with the potential to meet 50% of world energy demands and the requirement of reducing carbon emissions from fossil fuels [7]. Biomass energy systems can play an important role in a country's or region's development, i.e. education, employment and economic growth through business expansion (i.e. earnings), direct and indirect effects on GDP, support of traditional industries, rural diversification and community empowerment.

Not all the recoverable biomass in Bangladesh is available for electricity generation. Biomass is mainly utilised in the country as fuel for domestic cooking and for generating process heat in industrial and commercial activities. Estimation of the total national biomass availability and most importantly local resources in individual divisions and districts are important for assessing the potential for decentralised biomass electricity generation plants.

In this study, a review of the country's primary energy reserves, production and consumption; electricity generation and consumption; and renewable energy utilisation is presented. Potential biomass availability (annual, seasonal or monthly), both nationally and in individual districts, are estimated.

2. Bangladesh: location and economy

The People's Republic of Bangladesh—a south-Asian country—is located between 23°34′N and 26°38′N latitudes and 88°01′E and 92°41′E longitudes [8]. The country is divided into 6 divisions (regions): Dhaka, Chittagong, Rajshahi, Barisal, Sylhet and Khulna. In these regions, there are 64 districts (Fig. 1) [9]. The total area of the country is $1.44 \times 10^{11}\,m^2$ [10]. In 2003–2004, the population of Bangladesh reached 138.1 million (i.e., 959 people/km^2), making it the most densely populated country in the world. Of the total population, 80% resided in rural areas.

The climate in the country follows a four-season cycle: winter (December–February), summer (March–May), monsoon (June–September) and autumn (October–November). In winter, the average maximum and minimum temperatures are 26.5 and 13.5 °C, respectively, whereas the corresponding respective values in summer are 33.3 and 22.2 °C [11].

The sectors of the country's economy are agriculture and forestry, fishing, mining and quarrying, manufacturing, construction, electricity and gas, transport and communication, wholesale and retail trade, financial services and other services (e.g. tourism, real state business). During the last 5 years, Bangladesh averaged over 5% growth in the GDP. In the financial year 2003–04, GDP grew at an average rate of 5.5%—an increase of 20% over the previous year [12]. The agriculture and forestry sector—the single largest contributor to GDP growth—accounted for 31.5% of GDP in 1998–99, down from 34.5% in 1991–92. The crop sub-sector alone contributed 22.8% of GDP in 1998–99 compared with 27.9% in 1992–93 [13]. The national currency of the country is Taka, its exchange rate is US$1 = Taka 65.73 (as on 25/10/2005).

3. Commercial primary energy resources and use

Indigenous commercial primary energy resources of Bangladesh consist of the known reserves of natural gas and coal, and a limited hydroelectric capacity. The entire reserves of exploitable indigenous fossil fuels, with the exception of the coal reserve, are located in the eastern part of the country. This results in a gap of commercial energy supply between the east and the west.

Total commercial primary energy consumption in Bangladesh increased at an average rate of 0.74 mtoe per year between 1992 and 2004 (Fig. 2). The trend is mainly due the increased consumption of indigenous natural gas and imported oil. The contribution of hydropower to total commercial primary energy consumption is almost constant. In 2003

Fig. 1. Location, divisions and districts of the People's Republic of Bangladesh [9].

and 2004, the total national commercial primary energy consumption was 15.8 and 16.8 mtoe respectively [1]. In 2004, the shares of natural gas, oil, coal and hydroelectricity to total primary energy consumption were 70.8%, 25%, 2.4% and 1.8%, respectively [1].

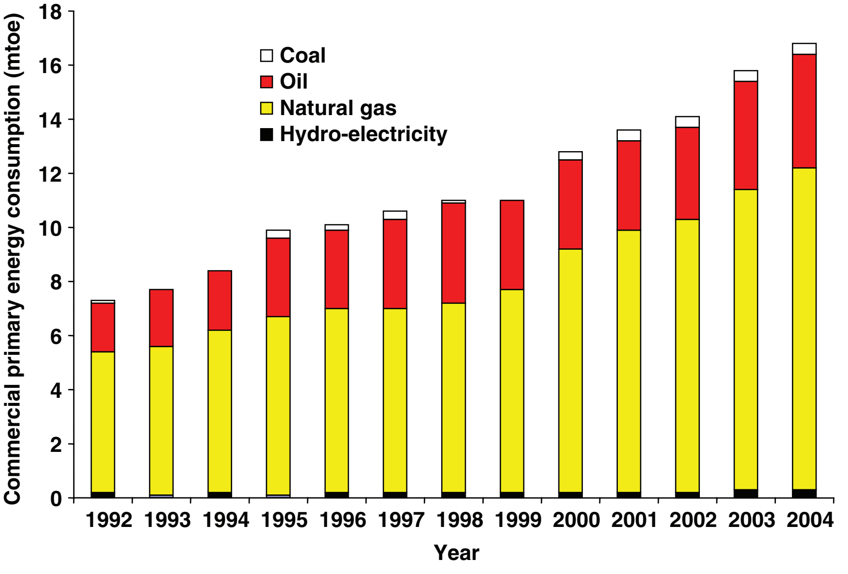

Fig. 2. Commercial primary energy consumption trends in Bangladesh [1].

Per capita annual energy consumption of commercial primary energy (i.e. fossil fuels and hydroelectricity) in Bangladesh, in 2003, was 0.114 toe [1]. This is one of the lowest in the world, compared with a world average of 1.556 toe/capita/year [1,14]. In 2002, the average consumptions for low-income countries and south-Asian countries were 0.493 and 0.468 toe/capita, respectively [14].

3.1. Natural gas

Natural gas plays an important role in the growth of the national economy. Of power generation 84.5% [4] and the whole of the urea fertiliser manufacturing are based on natural gas. Up to June 2004, 22 natural gas fields have been discovered in Bangladesh [15]. The total estimated amount of gas within these fields is 804.71 billion m^3, of which 580.78 billion m^3 is believed to be recoverable [15]. Up to June 2004, the cumulative total amount of gas produced was 157.03 billion m^3 (Table 2), resulting in a net recoverable gas reserve of 423 billion m^3.

Power plants, fertiliser factories, other industries (e.g. brick factories, tea processing plants, steel mills and textile factories), commercial organisations (e.g., offices and business centres) and the domestic sector are the end users of natural gas in the country (Fig. 3).

3.2. Oil

Bangladesh's only oil deposits, discovered in December 1986 and located at Haripur in the district of Sylhet, have an estimated reserve of 1.4 Mtonne of which 0.84 Mtonne are believed to be recoverable [16]. Up to July 1994, the cumulative total amount of crude oil produced was 0.0784 Mtonne [16]. Since then, oil production ceased because of the

Table 2
Natural gas fields of Bangladesh [15]

Name of the gas field	Natural gas reserve and production (billion m^3)			
	Total estimated reserve	Recoverable reserve	Cumulative production	Net recoverable
Bakhrabad	42.447	29.704	17.858	11.846
Habigonj	145.520	109.076	32.340	76.736
Jalalabad	33.839	23.701	5.401	18.300
Kailashtila	77.022	53.915	9.274	44.641
Meghna	4.842	3.370	0.933	2.437
Narshingdi	8.693	6.088	1.427	4.661
Rashidpur	56.690	39.672	9.189	30.483
Sylhet	19.369	13.564	4.915	8.649
Sangu	29.195	24.013	7.748	16.265
Salda Nadi	4.701	3.285	0.987	2.298
Titas	207.421	145.209	63.694	81.515
Beani Bazar	6.881	4.814	0.777	4.037
Fenchuganj	11.440	8.014	0.024	7.990
Begumgonj	1.331	0.934		0.934
Kutubdia	1.841	1.303		1.303
Semutang	6.428	4.248		4.248
Shahbazpur	18.831	13.167		13.167
Bibiana	89.056	67.989		67.989
Moulovibazar	12.714	10.194		10.194
Chatak	19.171	13.422	0.750	12.672
Kamta	2.039	1.416	0.597	3.084
Feni	5.239	3.681	1.119	0.297
Total	804.708	580.779	157.033	423.745

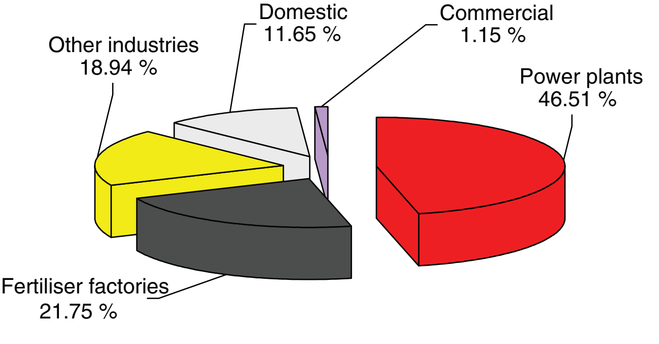

Fig. 3. Consumption of natural gas in Bangladesh in 2003–04 [15].

reduction of pressure in the field and the influx of water into the oil zone. In Bangladesh, oil is used mainly as a transport fuel, for some electricity generation and for industrial heating.

Table 3
Coal deposits in Bangladesh [17]

Coal deposit	Depth of coal layer (m)	Type of coal	Area (km^2)	Reserve (Mtonnes)
Jamalgonj, Jaipurhat	640–1158	Bituminous	11.66	1053
Baropukuria, Dinajpur	118–506	Bituminous	5.25	300
Khalashpir, Rangpur	257–451	Bituminous	5.75	400
Kuchma, Bogra	2381–2876	Bituminous		
Dighirpara, Dinajpur	250	Bituminous	15.00	
Phulbari, Dinajpur	>150	Bituminous		
Takerhat, Sunamgonj	45–97	Lignite		3

3.3. Coal

Substantial amounts of coal reserves, in seven fields [17], have been discovered in the north-western part of the country (Table 3). The major coal deposits are at Jamalgonj (in the Jaipurhat district), Baropukuria (in the Dinajpur district) and Khalashpir (in the Rangpur district). The total amount of coal reserve is estimated at 1.756 Gtonne [17].

Mining work has started only at Baropukuria. The Baropukuria coal mine was discovered in 1985 by the Bangladesh Geological Survey Department. Coal extraction from Baropukuria deposit, at an estimated rate of 1.0 Mtonnes/year, is expected to commence in the financial year 2004–05. Of the extracted coal, 70% will be used in a 250-MW coal-fired power plant [15,17].

3.4. Hydropower

Due to relative flatness of the country, Bangladesh has only a limited hydropower resource. The only 230 MW (comprising two 40 MW units and three 50 MW units) hydroelectric power plant, the Kaptai Dam located on the river Karnaphuli at Kaptai in the Chittagong district, was commissioned on 30 March 1962 [18]. It has a catchment area of $11 \times 10^3\,km^2$ and a reservoir capacity of $6.5 \times 10^9\,m^3$. The plant is operated by the Bangladesh Power Development Board (BPDB) and represents approximately 5% of the total national electricity generation installed capacity in 2003 [4]. In addition to power generation, the dam was constructed to provide the additional benefits of flood, irrigation and drainage and navigation control, as well as enhanced forest resource harvesting. Most of these objectives have been achieved to various degrees with the exception of irrigation and drainage control.

BPDB is considering a 100 MW capacity extension of this hydropower plant [19]. The additional energy will be generated during the rainy season when most of the year's water is spilled.

4. Electricity generation and consumption

BPDB was established in 1972 as a public-sector organisation with the responsibility for power generation, transmission and distribution of electricity throughout the country. Organisational changes were subsequently introduced to the transmission and distribution sectors. In 1977, the Rural Electrification Board (REB) was created and in 1991 the

Government of Bangladesh (GOB) established the Dhaka Electric Supply Authority (DESA) to operate and develop the distribution system in and around Dhaka and bring about improvements in customer service, collection of revenue and lessen the administrative burden on BPDB. To increase the efficiency of the distribution system and for better customer service, the GOB implemented different reform programmes. As part of such programmes, two companies, the Power Grid Company of Bangladesh (PGCB) and the Dhaka Electric Supply Company (DESCO), were established in 1996 and 1997, respectively [4]. The distribution network area of DESA has been re-defined, with some area being allocated to DESCO for better management. In December 2002, all distribution networks were transferred to PGCB, which is now the sole authority for operation, maintenance and extension of the distribution network in the country [15].

In order to develop the country's power sector, power generation and distribution were opened to both national and foreign private investments in 1996. This was followed by the formulation of 'Private Sector Power Generation Policy of Bangladesh' by the GOB. The involvement of Independent Power Producers (IPPs) was made effective after October 1996. The country's first private power plant (with a 110 MW installed capacity) started feeding power to the national grid in October 1998 [4,15].

4.1. Electricity generation and transmission

In 2003, the total installed electricity generation capacity was 4.68 GW and firm generation capacity was 3.7 GW [4]. Different types of power plants generate electricity and synchronise it with the national grid. In addition to grid-connected power plants, there are some isolated diesel engine power stations at remote areas and islands. The classification of the total installed capacity of both BPDB and IPP according to plant type

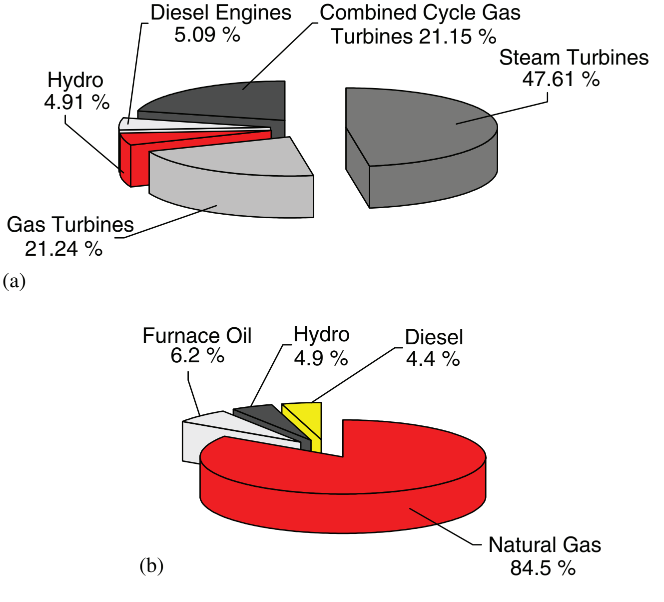

Fig. 4. Installed Capacity of power plants in Bangladesh in 2003 [4]: (a) according to plant type; and (b) according to primary energy source.

and fuel type are shown in Fig. 4. In 2003–04, the total electricity generated was 20.061 TWh, of which 12.583 TWh was generated by the public sector [15]. Per Capita electricity generation in 2002–03 and 2003–04 were 144 and 154 kWh, respectively [15].

The Jamuna–Padma–Meghna river system divides Bangladesh into east and west (Fig. 1). All natural gas fields are situated in the eastern part of the country. In this part, electricity is generated in gas-fired thermal power stations and a small percentage through hydropower. In the western part, imported oil is used for the generation of electricity. The fuel cost per kWh of the electricity generated in the western part is much higher than that in the eastern part. Low-cost electricity, generated in the eastern part, is transferred to the western part through the 230kV East–West Interconnector transmission line. BPDB owns and operate the high-voltage transmission network throughout Bangladesh. The transmission network is 5976 km long, comprising 230-kV and 132-kV lines. The total numbers of grid sub-stations in the country are 72, 10 of them are 230 kV and 62 are 132 kV, with a total capacity of 8.827 GVA [4].

4.2. Electricity consumption

Industrial and domestic sectors are the main consumers of the electricity [4]. Only 20% of the population (25% in urban areas and 10% in rural areas) are connected to grid electricity, with the vast majority (80%) being deprived of conventional supplies [20]. REB has been supplying electricity to rural areas through a number of Rural Electrification Societies, known as ‘Polly Biddut Samity’ (PBS). As of June 2004, 67 of these were operating commercially in the country. There are 5,394,736 customers in 41,125 villages. This required the installation of distribution lines with a total length of 173,125 km and 328, 33/11 kV grid sub-stations [21].

5. Renewable energy utilisation

In the context of Bangladesh, the main renewable energy resources are solar energy, biomass and wind power. There is some potential of mini/micro-hydropower, which could meet some of the local needs of electricity. No major studies have been undertaken to explore the potential of tidal, wave and ocean thermal energy resources. In Bangladesh, many academic institutions, government departments, non-governmental organisations and private companies, including BPDB, REB, Dhaka University (DU), Bangladesh Institute of Technology (BIT), Bangladesh University of Engineering and Technology (BUET), Bangladesh Atomic Energy Commission (BAEC), Local Government Engineering Department (LGED), Bangladesh Centre for Advanced studies (BCAS), Bangladesh Council of Scientific and Industrial Research (BCSIR), Bangladesh Rice Research Institute (BRRI), Bangladesh Rural Advancement Committee (BRAC), Rahimafrooz and Grameen Shakti (GS) are involved in R&D programme related to renewable energy technologies.

5.1. Wind energy

Few systematic wind speed surveys have been undertaken in the country. Bangladesh have a 724 km long coastline and many small islands (e.g. Saint Martin, Kutubdia, Swandip and Hatia) in the Bay of Bengal, where strong south-westerly trade wind and sea

breeze prevail in the summer months and there is gentle north-easterly trade wind and land breeze in the winter months.

Bangladesh Meteorological Department (BMD) is measuring wind speeds at different locations in the country at low heights for weather forecasting purposes, which is not sufficient for assessing the potential of harnessing wind power. A seasonal variation in wind speed prevails in the country, with a strong potential during April to September, and very weak potential during the rest of the year. Between June 1994 and June 1995, BMD measured wind speeds at a height of 20 m at Patenga in the Chittagong district, the most potential site for wind power harnessing in Bangladesh [22] (Table 4).

More recently, different studies have been undertaken to assess the wind energy resource of the country. In one such project, BCAS, in collaboration with LGED and the UK's Energy Technology Support Unit (ETSU), established the Wind Energy Study (WEST). The study was financially supported by the British Government and approved by the Aid Management Office, Dhaka (AMOD) in September 1995. ETSU provided BCAS with the necessary technical assistance. LGED helped in the installation of the wind monitoring masts, and facilitated the collection and despatch of data cards from the monitoring sites to BCAS headquarters at Dhaka on regular basis. After continuous measurement through 1996 and 1997 at seven selected sites (Fig. 5), the final report was published in January 1998 [23]. The average annual wind speed measured in the seven coastal stations ranged from 2.94 m/s to 4.52 m/s (Table 5). GTZ of Germany is also collaborating with REB of Bangladesh in conducting a parallel study [24] (Table 6). Wind speed measurements by WEST (Table 5) and GTZ (Table 6) confirmed that wind speeds are much higher in summer months (due to monsoon wind) than in winter months.

For estimating the wind energy potential, long-term systematic wind speed data is required. Under the Sustainable Rural Energy (SRE) programme, LGED in collaboration with BUET and BIT Chittagong has started the Wind Energy Resource Mapping (WERM) project. The study aims at assessing the wind energy potential of the country by systematic observation of wind regimes in initially 20 different suitable locations, including the Chittagonj Hill Tracts region, over a longer period of time [23,24].

Table 4
Wind speed measurements at Patenga (at 20 m height) [22]

Year	Month	Average wind speed (m/s)
1994	June	8.25
	July	7.81
	August	7.48
	September	6.93
	October	6.70
1995	January	6.43
	February	6.45
	March	7.37
	April	7.92
	May	8.47
	1–10th June	8.69

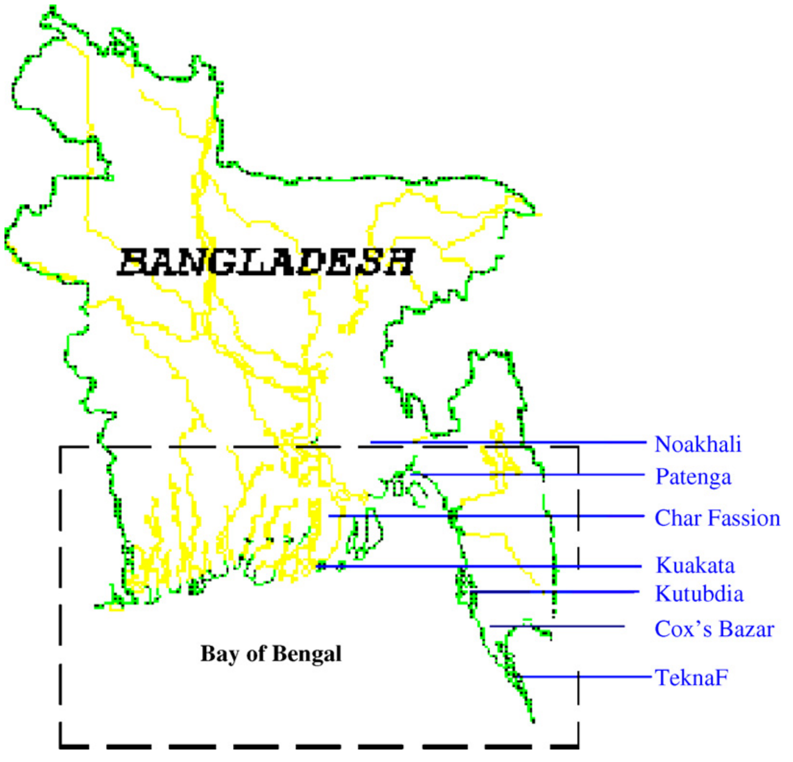

Fig. 5. Coastal regions: prospective area for wind energy utilization.

BPDB is installing a 10 MW grid-connected wind energy farm at Muhuri Dam in the Feni district. Plans are also underway for a 900 kW scheme at Moghnama Ghat in the Cox's Bazar district [4,23].

Small-scale wind turbine generators have been installed by GS and BRAC in coastal regions of the country. GS installed a 300 W Southeast Air Module (USA) unit and a 1.0 kW LMW (the Netherlands) unit at Chakoria in the Chittagong district. BRAC installed 11 wind turbine generators in various coastal sites. These systems supply power to some target groups to improve their standard of living [25].

Seasonal variation in wind speed poses some limitations to wind power generation and its widespread application in Bangladesh. However, most wind power potential sites in the country are situated in coastal regions, which are generally not connected to the national grid. Therefore, wind–solar–diesel or wind–diesel hybrid power generators offer practical systems for these regions. Four wind turbines, diesel generator and solar PV hybrid power stations have been installed by GS in the coastal areas of the Barguna district. Three of these have a capacity of 1.5 kW each, while the fourth has a capacity of 10 kW [26]. Under the SRE programme with the financial support from the United Nations Development Programme (UNDP), LGED installed 10 kW wind-solar hybrid systems at St. Martin island in the Bay of Bengal in the Chittagong district [23].

LGED and BCAS have been working on assessing the viability of wind pumps in Bangladesh. LGED installed a number of locally manufactured wind pumps, with a power

Table 5
Monthly average wind speeds at 25 m height at seven coastal stations measured by WEST [23]

Year	Month	Monthly average wind speed (m/s) at the monitoring stations stated						
		Patenga	Cox's Bazaar	Teknaf	Noakhali	Char Fassion[a]	Kuakata	Kutubdia
1996	June	8.75						
	July	5.87	5.42	5.77				
	August	5.32	5.33	4.90	4.70	5.20 (4.60)	5.70	
	September	3.36	3.69	3.46	2.94	3.34 (2.80)	3.77	3.58
	October	3.20	3.74	3.30	2.83	3.70 (3.07)	2.18	3.98
	November	2.61	2.93	2.29	1.91		1.98	3.23
	December	2.97	1.78	1.44	1.35	3.09 (2.38)	3.35	3.38
1997	January	3.25	2.33	1.99	1.31	2.80 (2.19)	3.18	3.67
	February	2.66	1.99	1.90	1.90	2.69 (2.02)	3.37	3.29
	March	3.13	2.42	2.26	2.38	3.54 (3.09)	4.84	3.53
	April	2.88	1.84	1.65	2.25	3.29 (2.28)	4.93	3.11
	May	4.96	3.97	3.09	3.99	4.81 (3.71)	6.28	4.89
	June	5.83	4.64	3.26	5.00	5.76 (4.42)	7.31	5.90
	July	5.67	4.80	4.33	4.92	5.22 (3.94)	7.34	6.17
	August	5.13	4.31	4.03	3.85	5.17 (4.01)		5.34
	September		2.96	1.83	2.77	3.08 (2.20)		3.97
Annual average		3.95	3.34	2.94	2.96	4.07 (3.21)	4.52	4.21

[a]Values in brackets represent wind speeds measured at 10 m height.

Table 6
Monthly average wind-speeds (m/s) at 20 m height at Patenga measured by GTZ [24]

Month	Year	
	1995	1996
January		
February		
March	6.7	
April	7.2	
May	7.7	8.0
June	8.1	6.9
July	8.0	8.4
August	7.4	3.5
September	6.8	3.9
October	6.2	3.2
November	4.4	2.6
December	4.2	2.2

output of 385 W at a wind speed of 4 m/s and a tower height of 8.4 m, at different locations including Tangail, Kustia and Cox's Bazar districts [23]. BCAS installed a 12-blade rotor and a 12.5-m high tower wind pump, designed by the Intermediate Technology (IT) Group of the UK and manufactured in Pakistan, in an agricultural field at Patenga in the

Chittagong district [25]. Daily water delivery has been found to vary, with an average daily water output, between November and January, of about 8 m^3. It appears that suitably-designed wind pumps can be extensively used for irrigation of vegetables in winter months in the coastal region. It is also possible to utilise them to harness underground fresh water for drinking in coastal islands [25].

5.2. Solar energy

The location of Bangladesh is ideal for tapping solar energy effectively. Daily solar irradiation intensity varies from 3 to 6 kWh/m^2 [22], with a maximum during March–April and a minimum in December–January. Monthly average daily solar irradiation intensities in different divisions of the country are shown in Table 7 [27].

Currently, BUET, BAEC, BCSIR, DU, BPDB, GS, BRAC, REB and a few other organisations are continuing their research to improve the performances of solar water heaters, solar cookers and solar dryers, and expand the use of solar thermal systems to new application areas. PV power systems are being accepted in Bangladesh gradually, but the slow progress achieved is due to their high initial capital cost. In 1981, BPDB installed 55 solar-powered warning lights on 11 towers of the East–West Interconnector at Aricha in the Dhaka district [28]. In 1983, Bangladesh Inland Water Transport Authority (BIWTA) installed 125 solar-powered beacon lights on shipping routes [28]. In 1988, BAEC installed a solar PV pilot scheme at Swandip Island in the Bay of Bengal for powering a beacon light on top of a watch tower, refrigerators in a veterinary hospital and a microphone and lighting in a local mosque [29]. Presently, BAEC is operating two solar PV water pumps for irrigation in the Dhaka and Moulovibazar districts [29].The Centre for Energy Studies (CES) of BUET is carrying out studies on solar PV utilisation. Low-cost improved lanterns (of capacity 5, 7.5 and 10 W) for home lighting in rural areas are being designed and tested at the Renewable Energy Research Centre (RERC) of DU [30].

Table 7
Monthly average daily solar irradiation intensity recorded at different divisions of Bangladesh from 1988 to 1998 [27]

Month	Monthly average daily irradiation intensity(kWh/m^2) at the division stated					
	Dhaka	Rajshahi	Sylhet	Bogra	Barishal	Jessor
January	4.03	3.96	4.00	4.01	4.17	4.25
February	4.78	4.47	4.63	4.69	4.81	4.85
March	5.33	5.88	5.20	5.68	5.30	4.50
April	5.71	6.24	5.24	5.87	5.94	6.23
May	5.71	6.17	5.37	6.02	5.75	6.09
June	4.80	5.25	4.53	5.26	4.39	5.12
July	4.41	4.79	4.14	4.34	4.20	4.81
August	4.82	5.16	4.56	4.84	4.42	4.93
September	4.41	4.96	4.07	4.67	4.48	4.57
October	4.61	4.88	4.61	4.65	4.71	4.68
November	4.27	4.42	4.32	4.35	4.35	4.24
December	3.92	3.82	3.85	3.87	3.95	3.97
Annual Average	4.73	5.00	4.54	4.85	4.71	4.85

5.2.1. Solar thermal systems

A variety of solar thermal systems have been developed and fabricated in the country, but these are yet to be commercialised. Examples of such systems include solar cookers, solar water heaters and solar dryers.

Solar cookers: Box-type and parabolic reflector-type solar cookers have been fabricated and tested in BCSIR and DU. The use of solar cookers in Bangladesh is possible during October to May. During the remaining four months of the year (June–September), it is often cloudy and the solar irradiation is therefore limited [31]. For cooking all over the year, an auxiliary fuel/energy source will be needed. RERC of DU developed a hybrid solar–electric box-type solar cooker [30]. One parabolic reflector-type solar cooker for a student hostel was designed and built by the Institute of Fuel Research and Development (IFRD) of BCSIR. It has a $48 \times 10^{-3}\,m^3$ cooking pot and the surface area of the reflector is about $8\,m^2$ [22].

Solar dryers: The Institute of Food Science and Technology (IFST) of BCSIR has developed a $1.85\,m \times 0.6\,m$ low-cost cabinet-type solar dryer. R&D work on solar dryers is continuing at BAU, ANANDO, BRRI and at IFRD of BCSIR [28].

Solar water heaters: In Bangladesh, various types of solar water heating systems have been designed, built and tested for potential use in hospitals, hotels and industries. These systems can raise the water temperature to 55–80 °C and have hot water storage capacities of $0.1–0.5\,m^3$ [30]. Design of such systems ranges from a simple earthen vat covered with polythene sheets to sophisticated, selectively coated flat-plate collector with double glazing of toughened glass [30].

5.2.2. Solar PV systems

Solar PV is a proven viable option in remote areas of Bangladesh. Applications of solar PV in the country include supplying electricity for homes, rural markets, health clinics, street lighting, water pumping and telecommunication. Solar home systems (SHSs), in particular, are gaining popularity in the country. Examples of SHSs installed in Bangladesh are shown in Table 8.

Some of the important solar PV installations in the country to date include the following:

- With a joined financing by the French and Bangladeshi Governments, $62\,kW_p$ solar PV project was commissioned by REB in 1996–97 for the electrification of rural homes and commercial enterprises in the four islands (Karimpur, Natunbazar, Alipur and Panchabati) of the Narshingdi district [21]. It is the single biggest solar PV project installed in the country. The project covered an area of $29\,km^2$ with about 8500 households in 21 villages. FONDEM from France carried out the initial design, and selected the sites, based on a socio-economic study and site surveys conducted by BCAS. Apex Inginierie of France supplied the solar modules and equipment and ARMCO, a local engineering firm, installed the entire system. A total of 795 PV systems of 5 variants, ranging in output from 6 to $92\,W_p$, were supplied and installed. The systems can be divided into two broad categories [21]:
  - Stand-alone systems: The users are provided with all the components, i.e. PV modules, storage battery, controller, wiring and the loads (e.g., lanterns, lamps, TVs, fans and refrigerators).
  - Charging station-based systems: All the components, with the exception of the PV modules, are provided to the users.

Table 8
Utilisation of solar home systems in Bangladesh [4,30]

Name of organisation	Number of systems and locations	Total installed electrical capacity (kW_p)
GS	42,000 all over the country	2150 kW
BRAC	10,456 all over the country	300.545 kW 40 W_p (20%), 50 W_p (60%) and 75 W_p (20%)
BPDB	300 at Juraichari, in the Rangamati district	54 kW
LGED	In different coastal areas	19.6 kW
SRE Programme of UNDP		33.8 kW
BCSIR	82	1.5 kW
REB	In the Narshingdi district	62 kW
Thengamara Mohila Sabuj Sangha (TMSS)	762	30–75 W_p each
CMES	618	2.85 kW
UBOMUS	400	
COAST Trust	352	
Integrated Development Foundation	601	
Srizony Bangladesh	1710	
Shubashati	592	
Singer Bangladesh Ltd.	31	
Anando	In the Khagrachari, Tangail and Cox's Bazaar districts	3.75 kW

This pilot project attracted the attention of a large number of international donor agencies (e.g. the World Bank, Asian Development Bank, USAID and Canadian International Development Agency) and acted as a flagship venture for the promotion of solar PV and other renewable energy projects.

- LGED has successfully completed the solar electrification of a market at Ganguita in the Jhenaidah district. The project was undertaken under the SRE programme of UNDP and implemented by LGED. The site has been selected for solar electrification because of its remote location (about 7 km away from the nearest grid connection), to replace a 5 kW diesel generator operated by a private entrepreneur. This is the first centralised solar PV system in Bangladesh. The PV system has an installed capacity of 1.8 kW_P with a daily energy output of 2 kWh, providing electricity to 45 shops, three small food processing facilities, a health centre and a bazaar mosque [30]. The responsibility of operation and maintenance has been entrusted to a local non-government organisation (NGO), Shubashati. The successful installation of the solar market electrification project represented a milestone for the green energy movement in the country.
- Another centralised 1.725 kW_p solar electrification project was implemented by LGED under the SRE programme at Nalitabari in the Sherpur district. It provides solar electricity to 60 houses, and has been operating successfully [30].

- The private Bangladeshi company Rahimafrooz Ltd installed the following solar PV systems for rural applications [32]:
  - solar PV lanterns and vaccine refrigerators;
  - small and medium stand-alone systems ($<3\,\mathrm{kW_p}$);
  - centralised solar PV power plant;
  - railway signaling systems;
  - telecommunication systems; and
  - navigation lightning systems.

One of these is the $1.2\,\mathrm{kW_p}$ solar PV system for powering the telephone exchanges in the coastal island of Char Fassion and Monpura in the Bhola district, with the financial assistance of the Government of Finland and the Telegraph and Telephone Board of Bangladesh [32].

- BPDB is currently implementing a three-phase solar PV project for the remote areas of Chittagong Hill Tracts region. The project consists of [4]:
  - 900 SHSs, with a capacity of $120\,\mathrm{W_p}$ each;
  - 30 sets of street lighting systems;
  - 3 sets of submersible water pumps ($50\,\mathrm{m^3}$/day/pump);
  - 9 sets of vaccine refrigerators for health clinics; and
  - 3 sets of $10\,\mathrm{kW_p}$ centralised solar PV market electrification systems for providing electricity to more than 200 shops in each market.

So far, the first phase of this project has been completed with the installation of 300 SHSs, 10 street lighting systems, one water pump, two vaccine refrigerators and one $10\,\mathrm{kW_p}$ centralised market electrification [4].

5.3. Small-scale hydropower

Worldwide small-scale hydropower projects have become more popular because of their low cost, reliability and environmental friendliness. Bangladesh has carried out a few surveys on its small-scale hydropower resources as a result of which it has been concluded that small-scale hydropower projects will be economically viable if combined with providing the additional benefits of flood and irrigation control, and encouraging tourism. In 1984, a group of Chinese experts identified 12 potential sites for small-scale hydropower generation in Bangladesh. Out of these, only one site at Mahamaya Chara, in the Chittagong district, has been considered for development of an integrated project for flood control, irrigation and power generation [24]. A working group has been set up by BPDB and BWDB to carry out groundwork of the scheme. The main objective of the project is to protect about $10.5\,\mathrm{km^2}$ of land from flood inundation during the monsoon season and to supply irrigation water during the dry season [4,19]. A dam is thus proposed to be constructed on the Mahamaya Chara. The reservoir water will be utilised for the generation of electricity by installing a water turbine at the foot of the dam.

A low cost $10\,\mathrm{kW_p}$ small hydropower plant was installed by Khoin, a local tribal man, at Monjaipara in the Bandarban District. A locally fabricated wooden turbine wheel was employed and the electricity generated was supplied to 40 homes. The unit attracted the attention of LGED and UNDP. LGED and Khoin carried out a joint study and identified

eight potential sites for small-scale hydropower generation in the southern hilly areas of Bangladesh [19,24]. At one of these sites (i.e. Bashkhali thana of the Chittagong district), the Bamer Chara Irrigation Project has been implemented by LGED for the provision and control of irrigation water to $3.55 \times 10^3\,km^2$ of land. A large reservoir has been built to provide irrigation water during the dry season. Water enters the project area through a gated spillway and the downstream flow is controlled by a conventional regulator. Currently, LGED is examining the flow rate in the spillway and exploring the scope for installing a small hydropower plant at the site. It is estimated that the proposed site has the potential to generate 20 MW of electricity [19]. Recently BPDB has submitted a proposal to the GOB for the installation of the following two small hydropower projects [4]: a 10 kW plant at Barkal in the Rangamati district and a 25 kW plant at the Teesta Barrage.

5.4. *Biomass energy*

Biomass energy is an important source of energy in most Asian countries. Substantial amounts of fuel wood, charcoal, agricultural residues, dung and leaves are used by households and industries. Main household applications are cooking and heating, whereas industrial applications range from food, mineral, textile and metal processing to miscellaneous applications such as road tarring and tyre re-treading. In addition to these heating applications, biomass fuels (e.g., bagasse and oil palm residues) are widely used for electricity generation or the co-production of electricity and steam in industry [33].

Consumption of conventional fuels and biomass in 16 developing countries in Asia is shown in Table 9. During the last decade, total annual primary energy consumption growth rate of these countries grew faster than the world average. The average annual growth rates ranged from 1.5% to 8% compared with the world average of 1.9% [34].

The energy potential of biomass resources has been assessed in some Asian countries (e.g. China, India, Srilanka, Thailand, and Malaysia) [6,35–37]. No such assessment has been carried out for Bangladesh. The principal biomass resources in the country are agricultural residues, animal waste, fuel wood, municipal solid waste and sewage sludge. In this section, the country's total amount of available biomass energy resources, in 2003, has been estimated. Not all biomass residues generated can be utilised for energy. In some instances, their wide dispersal or low bulk density makes recovery, transport and storage very costly. Residues may also be more valuable if used for purposes other than energy. One such use would be recycling residues onto the land, to help restore nutrients or reduce erosion. Residues might also be recovered for other domestic, industrial or agricultural uses, such as their use as building materials, for paper manufacturing or as animal fodder and bedding [38].

The total land area of Bangladesh is $1.3017 \times 10^{11}\,m^2$, of which 61.6% is arable land (Table 10). Bangladesh has a relatively low proportion of forest cover. In 2000, forests and woodlands represented only 10.2% of the total land area of the country compared with averages of 17.76% and 29.4% for Asia and the world, respectively [39]. Most of forest areas are located in the northern and eastern border parts of the country, as well as along the coast of the Bay of Bengal in the south [39].

Forests in Bangladesh are subject to heavy pressures in terms of both demands on wood production and competing land uses due to the large, increasing population. Total plantation area in the country was $3.32 \times 10^9\,m^2$ in 1990, of which $1.98 \times 10^9\,m^2$ was in the northern and eastern hills and $1.13 \times 10^9\,m^2$ in coastal regions [39]. The estimated planted forest area in the country in 2000 was $6.25 \times 10^9\,m^2$ [39] (Table 11). In order to achieve

Table 9
Annual primary energy consumption in 16 developing countries of Asia in 1993–1994 [34]

Country	Primary energy consumption (PJ/year)					Share of biomass to total primary energy (%)
	Conventional fuels	Biomass			Total primary energy	
		Fuel wood	Other biomass	Total biomass		
Bangladesh	210	141	363	504	714	71
Bhutan	2	12		12	14	86
Cambodia	14	79	3	81	95	86
China	23866	3290	4100	7390	31256	24
India	5822	2603	326	2929	8751	33
Indonesia	1978	818		818	2796	29
Lao PDR	5	42		42	47	89
Malaysia	898	93	3	96	994	10
Maldives	1	1		1	2	55
Myanmar	77	271		271	348	78
Nepal	23	192	64	256	279	92
Pakistan	1066	521	397	918	1984	46
Philippines	507	298	160	458	965	47
Sri Lanka	79	85	10	95	174	55
Thailand	1352	353	132	485	1837	26
Vietnam	260	423	393	816	1076	76

Table 10
Land use in Bangladesh in 2000 [10,39]

Type of land use	Area ($10^7\,m^2$)
Agricultural land	
Arable land[a]	8019
Permanent crops[b]	410
Permanent pasture[c]	600
Total	9029
Forests and woodlands	1334
Urban areas and mountains	2654
Total land area	13,017

[a]Land under temporary crops.
[b]Crops that occupy the land for long periods and need not be replanted after harvest.
[c]Land used permanently ($\geqslant 5$ years) for herbaceous forage crops.

a sustainable management of forest resources in Bangladesh, the Forest Master Plan of 1993, developed by the Bangladeshi Ministry of Environment and Forest, suggested an annual planting target of about $1.8\times10^8\,m^2$ during 1993–2002 and $2.1\times10^8\,m^2$ during

Table 11
Forest plantation areas in Bangladesh in 2000 by species groups [39]

Species group	Area of plantation		% of total area according to the type of plantation stated	
	$10^7\,m^2$	% of total area	Industrial	Non-industrial
Acacia spp.	32.0	5.1	48	52
Dalbergia	10.7	1.7	100	
Eucalyptus	37.3	6.0	48	52
Gmelina	21.3	3.4	48	52
Mahoganies	5.3	0.8	100	
Rubber	91.8	14.7		100
Teak	143.9	23.1	100	
Other broad leafed	282.5	45.2	48	52
Total	624.8	100.0		

2003–12 [40]. Potential areas for industrial plantation totalling about $7.0 \times 10^9\,m^2$ exist in the Chittagong and Sylhet divisions [39].

5.4.1. Biomass resources

The economy of Bangladesh depends principally on agriculture. The main crops produced are rice, sugar cane, vegetables, wheat, jute, pulses, coconuts, maize, millet, cotton and groundnuts (Table 12). Agricultural crops generate large quantities of residues. Such residues represent an important source of energy both for domestic as well as industrial purposes. Other sources of biomass in the country are farm-animal wastes and poultry droppings produced by the national herds (Table 13), fuel wood from existing forests, tree residues and saw dust from the forestry industry (Table 14). The 138.1 million citizens of Bangladesh [43] produce huge amounts of human waste and municipal solid waste (MSW) annually.

Agricultural residues: There are two types of agricultural crop residues: field residues and processing residues. Studies in some neighbouring Asian countries [6,34] produced useful residue-to-yield ratios for several agricultural crops. These ratios have been employed in this study, together with published productivity figures for the individual crops (Table 12), in order to estimate the rate of generation of the corresponding residues in Bangladesh (Table 15). Crop residues can be collected, mostly by bailing, either at the same time or after the primary crop has been harvested. Not all field residues are recoverable. The percentage of field residues of a crop to be recycled onto the land depends upon the specific local climatic and soil conditions [46]. There is no available specific data concerning the common practices in Bangladesh or the neighbouring Asian countries. However, in developed countries, it has been established that only 35% of field crop residues can be removed without adverse effects on future yields [46]. Crop processing residues, on the other hand, have a 100% recovery factor. Accordingly, it is estimated that the total annual amount of recoverable agricultural-crop residues in Bangladesh is 41.994 Mtonne, of which 62.5% are field residues and 37.5% are process residues (Table 15).

Animal wastes and poultry droppings: Manure from cattle, goats, buffaloes and sheep are the common animal wastes in Bangladesh. The quantity of waste produced per animal per day varies depending on body size, type of feed and level of nutrition. The annual

Table 12
Annual yield of agricultural crops in Bangladesh in 2003 [10]

Crop	Annual production rate[a]
Rice	39.090
Sugarcane	6.838
Vegetables (total)	1.837
Wheat	1.507
Jute	792.000
Pulses (total)	345.000
Coconut	88.000
Millet	57.000
Cotton[b]	45.000
Groundnut	34.000
Maize[b]	10.000

[a]Annual production rates for rice, sugarcane, vegetables and wheat are in Mtonne/year. For the rest of the agricultural crops the production rates are in ktonne/year.
[b]Annual production of rates of cotton and maize is not available for 2003, so production rates of 2002 were used.

Table 13
Number of heads of national herds of farm animals and poultry in Bangladesh in 2003 [10]

Species	Number of heads (millions)
Farm animals	
Cattle	24.500
Buffaloes	0.850
Goats	34.500
Sheep	1.260
Poultry	153.000

Table 14
Annual rates of waste generated by the forests and the forestry industry in Bangladesh

Biomass resource	Annual production rate		Moisture content		Annual production rate (Mtonne dry matter)
	(Mtonne)	Reference	(% by mass)	Reference	
Fuel wood	6.932	[39]	20	[6]	5.546
Tree residues	1.821	[41]			1.821
Sawdust	0.118	[42]	20	[6]	0.094

production rates of animal wastes and poultry droppings were estimated by employing the number of heads of the national herds (Table 13) and the waste generation rate per head for the individual species as estimated in neighbouring Asian countries (Table 16). In 2003, total population of chicken and ducks in Bangladesh were 140 and 13 million head respectively [10]. There are two types of chicken, broilers and layers. Individual population data, however, is not available. The average amount of droppings (on air dry basis) produced by broilers and layers are 0.02 and 0.03 kg/bird/day respectively [47].

Table 15
Generation and recoverable amounts of agriculture-crop residues in Bangladesh in 2003

Biomass	Residues-to-yield mass ratio		Residues generation rate (ktonne/year)	Residues recovery rate (ktonne/year)	Moisture content		Residues recovery rate (ktonne dry matter/year)
	Value	Reference			(% by mass)	Reference	
Field residues							
Rice straw	1.695	[6]	66,258	23,190	12.7	[6]	20,245
Wheat straw	1.75	[34]	2637	923	7.5	[45]	854
Sugarcane tops	0.3	[34]	2051	718	50	[33]	359
Jute stalks	3	[34]	2376	832	9.5	[45]	753
Maize stalks	2	[34]	20	7	12	[45]	6
Millet stalks	1.75	[34]	100	35			35
Groundnut straw	2.3	[34]	78	27	12.1	[33]	24
Cotton stalks	2.755	[34]	124	43	12	[45]	38
Residues from vegetables[a]	0.4	[44]	735	257	20	[44]	206
Residues from pulses[a]	1.9	[44]	656	229	20	[44]	184
Subtotal			75,035	26,261			22,704
Process residues							
Rice husk	0.267	[6]	10,437	10,437	12.4	[6]	9143
Rice bran	0.083	[6]	3244	3244	9	[45]	2952
Sugarcane bagasse	0.29	[34]	1983	1983	49	[6]	1011
Coconut shells	0.12	[34]	11	11	8	[45]	10
Coconut husks	0.41	[34]	36	36	11	[45]	32
Maize cob	0.273	[34]	3	3	15	[45]	3
Maize husks	0.2	[34]	2	2	11.1	[33]	2
Groundnut husks	0.477	[34]	16	16	8.2	[33]	15
Subtotal			15,732	15,732			13,168
Total residues			90,767	41,994			35,870

[a]Assuming all residues are process based.

Table 16
Generation and recoverable rates of animal wastes and poultry droppings in Bangladesh

Biomass	Rate of generation			Waste recovery rate (Mtonne dry matter/year)
	(kg dry matter/capita/day)	Reference	(Mtonne dry matter/year)	
Animal waste				
Cattle	2.86	[48]	25.576	15.345
Buffaloes	2.52	[48]	0.782	0.469
Goats	0.55	[48]	6.926	4.156
Sheep	0.33	[48]	0.152	0.091
Subtotal			33.436	20.061
Poultry droppings	0.02	[47]	1.117	0.558
Total			34.552	20.619

A conservative estimate of the national production rate of poultry droppings can be achieved by considering that all the chickens are of broiler type and production rate for ducks is the same as for chicken. The recovery/collection factors for animal waste and poultry droppings were considered to be 60% and 50%, respectively [47,48]. Accordingly, it is estimated that the total annual amount of recoverable animal wastes and poultry droppings in Bangladesh is 20.619 Mtonne (Table 16).

Human waste and MSW: The total rate of human waste generation by the 138.1 million citizens [43] in Bangladesh has been estimated as 4.537 Mtonne of dry matter/year (corresponding to 0.09 kg/capita/day) [48]. Compared with an average MSW generation rate of 0.4 kg/capita/day in Indian cities [48], in urban areas of Bangladesh the rate is between 0.4 and 0.5 kg/capita/day [49]. In rural areas of the country, the generation rate is only 0.15 kg/capita/day [49]. Rural and urban population data are available for 1998 [8]. By assuming a similar rural-to-urban population ratio in 1998 and 2003, ratio, rural and urban population in 2003 can be estimated as 108.56 and 29.54 million, respectively, in 2003. Considering that human waste and MSW are 100% recoverable, the total annual amount of the biomass available from these two sources in Bangladesh is 14.793 Mtonne (Table 17).

Forests and the forestry industry: Deforestation, environmental degradation, the growing demand for traditional energy and the lack of development in the forestry sector are serious concerns for the government and the people of Bangladesh. Employment of the ever-increasing rural labour force is dependent on the growth of rural industries, which are very much dependent upon the existence of a sustainable supply of biomass fuel, especially fuel wood. The forest land is unevenly distributed in the 64 districts of the country. Locations of Bangladesh forest are shown in Table 18. Forest biomass includes tree components such as trunk, branches, foliage and roots. Tree trunks and main branches constitute what is commonly known as fuel wood. Twigs, leaves, bark and roots are tree residues. Total fuel wood production in Bangladesh in 2003 was 6.932, Mtonne [39]. Estimates for the rate of supply of tree residues in recent years are not available; in 1992, it was 1.821 Mtonne [41]. Both wood processing residues (e.g. sawmill off-cuts and sawdust) and recycled wood (e.g. that derived from the demolition of buildings, pallets and packing

Table 17
Generation and recoverable rates of human waste and MSW in Bangladesh in 2002 [48,49]

Biomass	Rate of generation[a]		Waste recovery rate (Mtonne/year)	Moisture content		Waste recovery rate (Mtonne dry matter/year)
	(kg/capita/day)	(Mtonne/year)		(% by mass)	Reference	
Human waste	0.09	4.537	4.537			4.537
MSW						
Urban	0.4	4.312	4.312	45.0	[49]	2.372
Rural	0.15	5.944	5.944	45.0	[49]	3.269
Subtotal MSW		10.256	10.256			5.641
Total		14.793	14.793			10.177

[a]Calculation of human waste generation rate is based on dry matter.

Table 18
Forest type and location in Bangladesh [41]

Forest type	District
Mangrove forest (tropical evergreen)	
Sundarbans	Khulna and Satkhira
Coastal	Cox's Bazaar, Chittagong, Noakhali, Barishal, Patuakhali and adjacent coastal districts
Hill forest (tropical moist evergreen)	Chittagong, Sylhet, Comilla, Rangamati, Bandarbon and Khagrachari
Plain land sal forest (tropical moist deciduous)	Dhaka, Tangail, Mymensingh, Dinajpur

Table 19
Annual generation and recoverable rates of biomass from different sources in Bangladesh

Biomass resource	Rate of generation (Mtonne/year)	Waste recovery rate (Mtonne/year)	Waste recovery rate (Mtonne dry matter/year)
Crop residues			
Field residues	75.035	26.261	22.704
Process residues	15.732	15.732	13.168
Animal wastes and poultry droppings	34.552	20.619	20.619
Human wastes and MSW	14.793	14.793	10.177
Forests and forestry industry	8.871	8.871	7.461
Total	148.983	86.276	74.129

crates) are important sources of energy. The annual amount of such recycled wood, on a sustainable basis, is, however, not known. It has been estimated that only about 20% of a tree, initially harvested for timber, results in sawn products. The remaining 80% is discarded, in equal proportions, as forest residues and process residues (i.e. bark, slabs, sawdust, trimmings and planer shavings) [34]. Ply mills produce about the same amount of residues as sawmills [34]. In 1998, 0.118 Mtonne of sawdust was available for energy purposes [42]. Considering 100% recovery rate, the annual amount of recoverable biomass from forests and forestry industry in Bangladesh is 8.871 Mtonne (Table 14).

5.4.2. Total energy potential of recoverable biomass resources

The total annual generation and recoverable rates of biomass in Bangladesh are 148.983 and 86.276 Mtonne/year, respectively (Table 19). Agricultural residues represent 48.7% of the total recoverable biomass, followed by a 23.9% contribution from animal wastes and poultry droppings. Using the lower calorific values of the individual biomass components, the energy potential of the annually recoverable 86.276 million tonne of biomass is estimated at 1125.4 PJ (Table 20), which is equivalent to 26.795 mtoe or 312.613 TWh.

5.4.3. Biomass consumption

In Bangladesh, biomass is used as an energy source as well as for non-energy purposes. It is widely utilised in both rural and urban areas of the country, as a domestic fuel for cooking and heating. Many commercial and industrial facilities employ biomass for the provision of process heat. In addition, some quantities of biomass are used as animal fodder, animal bedding, building material, material for furniture making and as an organic soil conditioner (i.e. fertiliser). There is no available data for the rates of biomass consumption for these non-energy uses. It is, however, believed that the amount of biomass involved represents a small proportion of the total consumption figure, and, therefore, will not be considered in this study.

The pattern of utilisation of biomass for energy varies from one region of the country to another, depending on the prevailing socio-economic conditions and the availability of commercial fuels [51,52]. An estimate for the annual rates of consumption of biomass for energy in Bangladesh is presented in Fig. 6. Domestic cooking, particularly in rural areas, represents the largest single consumer of biomass. Table 21 presents statistical data for total biomass energy consumption in some developing countries in Asia. Although the use of biomass energy per capita in Bangladesh exhibited an average decreasing trend between 1981 and 1991 and was below the regional average in 1991, the total biomass consumption has increased as a result of the rapid population growth. Many other developing Asian countries have experienced similar trends [54].

5.4.4. Biomass energy available for electricity generation

In 1991, the biomass consumption for energy in Bangladesh was estimated as 276.6 PJ (or ~6.6 mtoe) [54] (Table 21). At an average annual growth rate of 1.3%, the consumption in 2003 was estimated to be 319.75 PJ (or ~7.613 mtoe). The total available recoverable biomass energy of the country in 2003 was estimated as 1125.407 PJ or 26.795 mtoe (Table 20). Accordingly, in 2003, 805.657 PJ or 223.794 TWh of biomass energy was available for the generation of electricity. On the other hand, the total biomass energy consumption was estimated in 1998 at 435.204 PJ (or ~10.362 mtoe) [45]. Assuming

Table 20
Energy potential of biomass resources in Bangladesh

Biomass	Recovery rate (ktonne/yr)	Recovery rate[a] (ktonne dry matter/yr)	Lower calorific value (GJ/ tonne)	Lower calorific value Reference	Energy content (PJ)
Field crop residues					
Rice straw	23,190	20,245	16.30	[6]	329.994
Wheat straw	923	854	15.76	[45]	13.459
Sugarcane tops	718	359	15.81	[34]	5.676
Jute stalks	832	753	16.91	[45]	12.733
Maize stalks	7	6	14.70	[45]	0.088
Millet stalks	35	35	12.38	[34]	0.433
Groundnut straw	27	24	17.58	[33]	0.422
Cotton stalks	43	38	16.40	[45]	0.623
Residues from vegetables	257	257	13.00	[44]	3.341
Residues from pulses	229	229	12.80	[44]	2.931
Subtotal	26261	22704			369.700
Process crop residues					
Rice husk	10,437	9143	16.30	[6]	149.031
Rice bran	3244	2952	13.97	[34]	41.239
Sugarcane bagasse	1983	1011	18.10	[34]	18.299
Coconut Shells	11	10	18.53	[34]	0.185
Coconut husks	36	32	18.53	[34]	0.593
Maize cob	3	3	14.00	[45]	0.042
Maize husks	2	2	17.27	[45]	0.035
Groundnut husks	16	15	15.66	[33]	0.235
Subtotal	15,732	13,168			209.659
Total agricultural-crop residues	41,994	35,870			579.359
Other biomass					
Animal waste	20,061	20,061	13.86	[50]	278.045
Poultry droppings	558	558	13.50	[47]	7.533
Human waste	4537	4537	10.60	[45]	48.092
MSW	10,256	5641	18.56	[45]	104.697
Fuel wood	6932	5546	15.00	[45]	83.190
Tree residues	1821	1821	12.52	[41]	22.799
Sawdust	118	94	18.00	[45]	1.692
Total					1125.407

[a]Moisture content is 20% by mass for residues from vegetables and pulses.

the same average annual growth rate of 1.3%, the biomass consumption in 2003 would have been 463.492 PJ (or ~14.484 mtoe). Based on this estimate, the amount of biomass energy available in 2003 was 661.915 PJ, which is equivalent to 183.865 TWh. According to these two estimates and considering that the consumption of biomass for non-energy purposes is negligible, the annual available biomass energy potential for electricity generation in Bangladesh is in the range of between 183.865 and 223.794 TWh.

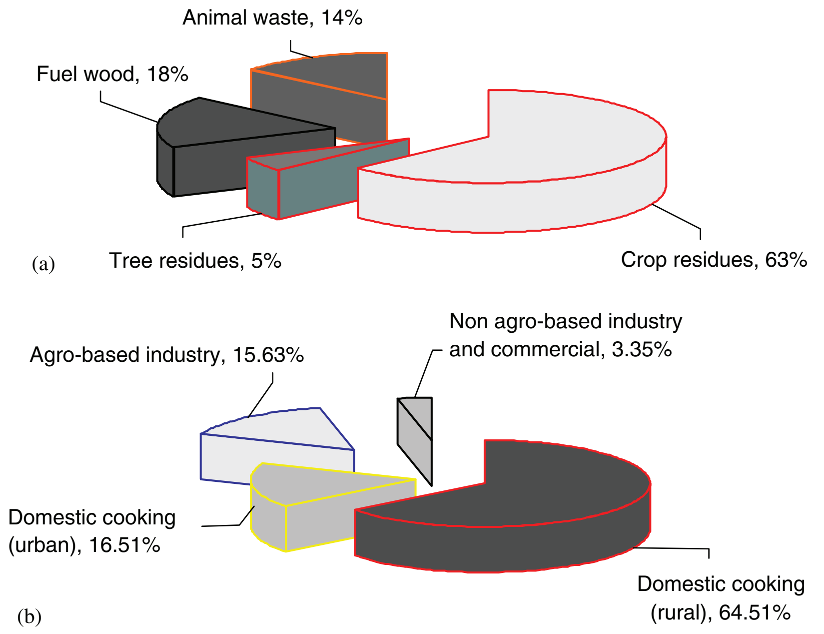

Fig. 6. Biomass consumption for energy in Bangladesh [53]: (a) according to biomass source; and (b) according to consumer sector.

Availability of the biomass resources in the individual districts are needed for planning off-grid decentralised sustainable biomass electricity generation in Bangladesh. Generation rates of agricultural residues in the districts are not available for all types of crops. Figures for the rates for rice, wheat, jute, sugarcane, vegetables and pulses have been reported for 1998 [8]. Rural and urban population in 1998, and the number of farm animals and poultry heads in 1996 [8,55] are the only available data on district level. The corresponding figures for 2003 have been estimated by assuming that the trend in individual districts followed the average national trend in the same period. Data concerning biomass generation from forests and the forestry industry in individual districts are non-existent. Only forestry areas in 1998 are available [8]. The proportion of the forestry area in individual districts to the national total was assumed to remain the same in 2003. Accordingly, an approximate value of the forestry biomass in each district in 2003 was calculated by employing the total national generation rates of the forestry residues in the country in that year. The rate of biomass consumption in individual districts has been assumed to be the same as the national average (i.e. 3.356 GJ/capita/year) and to follow the same pattern as that presented in Fig. 6(a). Following these assumptions, biomass availability for electricity generation in all districts has been estimated (Table 22). The detailed results of the two districts with the highest total biomass energy potentials (i.e. Serajganj and Pabna) are presented in Table 23.

In many developing countries, the efficiency of utilisation of biomass in traditional systems is very low. Tables 24 and 25 present reported figures for the efficiencies of typical household stoves used in Asia [56,57]. A large amount of biomass can be saved annually in Bangladesh by employing improved (i.e. more efficient) cooking stoves, furnaces, boilers and other devices consuming biomass fuels. The traditional mud cooking stoves

Table 21
Biomass energy consumption in some Asian developing countries in 1991 and the average annual rate of growth in the period 1981–1991 [54]

Country	Population (millions)	GDP (US$/capita)	Biomass annual consumption rate					
			Total		Per capita		Per unit of GDP	
			(PJ)	Average annual growth rate (%)	(GJ/capita)	Average annual growth rate (%)	(GJ/US$)	Average annual growth rate (%)
Bangladesh	116.4	176	276.6	1.3	2.4	−1.2	13.5	−2.7
Bhutan	1.6	200	11.7	4.8	7.4	2.6	37.2	−1.6
Cambodia	8.6		5.4	2.7	0.6	0.0		
China	1170.7	337	2017.8	2.7	1.7	1.2	5.1	−5.9
India	862.7	370	2823.7	2.7	3.3	0.6	8.8	−2.4
Indonesia	187.7	523	1464.8	2.2	7.8	0.2	14.9	−3.1
Lao PDR	4.3	310	38.5	2.8	8.9	−0.1	28.7	
Malaysia	18.3	2449	90.2	2.7	4.9	0.0	2.0	−3.3
Myanmar	42.7	243	192.8	2.1	4.5	0.0	18.5	1.0
Nepal	20.1	166	205.7	6.2	10.2	3.3	61.6	1.6
Pakistan	121.5	341	296.2	4.4	2.4	1.1	7.1	1.5
Philippines	63.8	596	381.8	2.2	6.0	−0.3	10.0	1.0
Sri Lanka	17.4	455	89.4	2.5	5.1	1.0	11.3	1.6
Thailand	55.4	1334	526.4	0.8	9.5	−0.6	7.1	6.6
Vietnam	68.1	721	250.8	2.4	3.7	0.3	5.1	

Table 22
Annual biomass availability for electricity generation in individual divisions of Bangladesh

Division	Availability of biomass (in ktonne dry matter) according to the source stated				
	Agricultural wastes and forestry residues	MSW	Animal wastes	Poultry wastes	Human excreta
Barisal	−440.61	353.08	940.37	62.13	312.50
Chittagong	4584.69	1108.40	1486.96	118.67	884.38
Dhaka	−2240.35	1928.60	2709.72	127.50	1397.85
Khulna	2848.38	659.98	1765.05	67.50	537.45
Rajshahi	12396.90	1273.58	4179.45	150.63	1114.99
Sylhet	−150.51	317.26	811.54	32.01	289.41

used in Bangladesh exhibit overall efficiencies of only between 5% and 10% [58]. A number of improved stoves have been developed at the IFRD of BCSIR. These have been classified as [58]:

- improved stoves without chimney, which save 50–55% fuel compared with traditional stoves,
- stoves with chimney, with fuel savings of 60–65% and
- stoves with waste heat recovery.

Table 23
Biomass available for electricity generation in the Serajganj and Pabna districts of the Rajshashi division

Biomass resource	Serajganj		Pabna	
	ktonne dry matter/year	PJ/year	ktonne dry matter/year	PJ/year
Farm animal waste	240.10	3.328	224.23	3.108
Poultry droppings	10.73	0.145	8.40	0.113
MSW	107.16	1.989	95.48	1.772
Human excreta	96.49	1.023	81.28	0.862
Agricultural waste	6957.83	113.590	6150.22	100.813
Forests and forestry industry residues	−151.12	−1.773	−127.32	−1.495
Total[a]	7261.19	118.300 (32.861)	6432.28	105.173 (29.215)

[a]Figures between brackets represent biomass energy in TWh/year.

Table 24
Efficiencies of typical household stoves in South Asia [56]

Fuel	Combustion efficiency (%)	Overall efficiency (%)
Biogas	99	57
LPG	98	54
Kerosene	98	50
Fuel wood	90	23
Crop residues	85	14
Dung	85	11

IFRD has been engaged in a pilot-scale dissemination of improved model biomass-fired stoves, capable of saving 50–70% of fuel compared with traditional stoves, all over the country [58]. These improved stoves are gradually gaining popularity.

Biomass briquettes have the main advantages of easy transportation, better handling, cleaner and more efficient combustion, and higher volumetric calorific value of the fuel. It also produces a fuel that is suitable for a variety of applications. Briquetting of sawdust and other agro residues has been practised for many years in several countries. Briquettes can be produced with a density of 1200–1400 kg/m^3 compared with a corresponding value of 500–700 kg/m^3 for common wood. Accordingly, savings of diesel fuel during the transportation of residues or wood are substantial: a 10 tonne truck can transport 3–4 times more weight of briquette than loose biomass fuel [59]. There are two types of machines used for briquetting the biomass: piston presses (also known as die and punch machines) and screw extruders. The screw extruder technology has proved to be successful in briquetting rice husk and saw dust in Europe, Japan, Malaysia, Taiwan and Thailand [60]. The machines operating in Bangladesh are of heated-die-type of which a total of 906 biomass briquetting machines are currently in operation [42].

Table 25
Efficiencies of household stoves in India [57]

Type of stove	Biomass fuel	Combustion efficiency (%)	Heat transfer efficiency (%)	Overall efficiency (%)
Open and three-stone fire places	Fuel wood	90–92	20	18
Solid stoves with or without chimney	Fuel wood	80–91	15–29	14–24
	Agricultural residues	77–90	11–14	10–14
	Animal waste	82–89	10	9
Portable ceramic or pottery stoves	Fuel wood	89	33	29
	Agricultural residues	86	22	19
	Charcoal	85	20	17
	Animal waste	88	15	13
Portable ceramic/metal stoves	Fuel wood	91	24–29	21–26
	Agricultural residues	91	24	22

6. Conclusions

The GOB has recognised the importance of renewable energy in its 'Energy Planning Programme' and the drafting of the 'Renewable Energy Policy' [61]. Solar and wind energy in Bangladesh are characterised by high investment cost, and seasonal and site dependency. Biomass is a major energy source in Bangladesh, which can be used for decentralised electricity generation. Worldwide, biomass-to-electricity generation has gained importance due to employment opportunity, reduction in reliance on fossil fuels and positive environmental benefits.

The current study indicates that in 2003, the national total annual generation and recoverable rates of biomass in Bangladesh were 148.983 and 86.276 Mtonne, respectively. Of the total recoverable amount, agricultural residues represent 48.7%, followed by a 23.9% contribution from animal wastes and poultry droppings. In energy terms, the national annual amount of the recoverable biomass is equivalent to 312.613 TWh. Considering the present national consumption of biomass, the total available biomass resource for electricity generation is in the range of between 183.865 and 223.794 TWh. The results obtained show that all districts, with the exception of Dhaka, have considerable amount of available resources of animal wastes, poultry wastes, MSW and human excreta. Currently, not all districts have the potential to utilise agricultural and forestry residues for electricity generation. However, with the implementation of the ongoing improved-stoves installation programme of the GOB and utilisation of more energy efficient devices, it is expected that most districts will have considerable amounts of these residues for electricity generation. In 2003, Serajganj had the highest total biomass availability potential of 32.861 TWh, followed by Pabna with 29.215 TWh.

The World Bank has estimated that Bangladesh loses around $1 billion/year due to power shortages and unreliable power supply [20]. The GOB has a vision to electrify the whole of the country by the year 2020. Electrification of villages in remote areas usually leads to large investment and power losses associated with transmission and distribution

networks. Small- to medium-scale biomass-based electricity generation systems provide a good prospect for supplying electricity economically and sustainably to rural and remote areas in Bangladesh. This will make a significant contribution towards the achievement of the government target of total electrification of the country by the year 2020.

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